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ORIGINAL PAPER

# Role of unbalanced slab resistive force in the 2004 off Sumatra mega-earthquake ( $M_w > 9.0$ ) event

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**Abstract** Present study addresses the role of major plate-driving forces, particularly the slab pull and slab resistive forces, for the generation of 26 December 2004  $M_w > 9.0$  off Sumatra megathrust earthquake. Major controls on the plate-driving forces are normally visualized through age, speed, and average dip of the slab during subduction. Wide variation in age, plate obliquity, stress obliquity, subduction rate, dip angle, and flexing depth of the subducting oceanic lithosphere between Andaman and Sumatra thus allowed us for quantitative evaluation of the slab pull ( $F_{SP}$ ) and slab resistive ( $F_{SR}$ ) forces in three well-defined sectors (I, II and III). Computed values of these forces in the three sectors: (1)  $F_{SP} = 1.29 \times 10^{13}$  N/m,  $F_{SR} = 1.41 \times 10^{13}$  N/m; sector I, (2)  $F_{SP} = 2.10 \times 10^{13}$  N/m,  $F_{SR} = 1.13 \times 10^{13}$  N/m; sector II, and (3)  $F_{SP} = 2.08 \times 10^{13}$  N/m,  $F_{SR} = 2.72 \times 10^{13}$  N/m; sector III clearly suggest a spatial variation of stress regime in the subducting oceanic lithosphere. Excess  $F_{SR}$  in sectors I and III are interpreted as the causative forces behind the triggering of major seismic energy bursts near Sumatra and Andaman on 26 December 2004. A gap of minimum seismic energy burst near Great Nicobar possibly was controlled by the excess of  $F_{SP}$  in sector II. This study further advocates that the cyclic stress, resulted from unbalanced component of slab resistive force, had a definite control on the occurrence of 2004 off Sumatra megathrust earthquake around the flexing zone of the subducting lithosphere.

**Keywords** Megathrust earthquake · Flexing zone · Slab pull force · Slab resistive force · Stress loading

## Introduction

Since the inception of continental drift and sea-floor spreading hypothesis, Earth scientists were principally involved in evaluating the kinematics of plate motions vis-à-vis the theory of plate tectonics. After the introduction of plate guiding stresses (Elsasser 1969) and formulation of plate tectonics (McKenzie 1969), several scientists (Forsyth and Uyeda 1975; Harper 1975; Solomon et al. 1975) were encouraged in understanding the plate kinematics, and subsequently, driving mechanisms of lithospheric plates were evolved. Incidentally, Isacks and Molnar (1969) interpreted quite convincingly the occurrence of mantle earthquakes in the backdrop of plate tectonics, and several hypothesis were put forward over more than three decades to appreciate the geological processes behind the occurrence of great to mega-earthquakes at the shallower part ( $<60$  km) of the subducting lithosphere at the plate margins around the world. In this connection, Forsyth and Uyeda (1975) first suggested that the slab pull ( $F_{SP}$ ) and slab resistive ( $F_{SR}$ ) are the major plate-driving forces apparently control the dynamic equilibrium of the plates, and successfully explained the spatial variation of stress regime in the subducting oceanic lithosphere. They also invoked that  $F_{SP}$  and  $F_{SR}$  along the longitudinal profiles of the descending plate dictate the major intraplate failure for mega-earthquake generation ( $M_w \geq 8.5$ ) at the shallower level of the lithosphere (Forsyth and Uyeda 1975; Khan and Chakraborty 2009). Further, the flexing zone of the lithosphere beneath the trench during subduction suffers instability by the net effect of slab pull and slab resistive forces (Marotta and Mongelli 1998), and  $\sim 60\%$  of the energy associated with the subducting slab is normally dissipated through the bending segment of the slab (Conrad and Hager 1999). Invariably recorded shallowest

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dip, lowest flexing depth (Widiyantoro and Van der Hilst 1997; Khan and Chakraborty 2005), youngest plate age ( $\sim 47$  Ma in northwest Sumatra, increases to  $\sim 152$  Ma towards east near Java and  $\sim 67$  Ma towards north near North-Andaman, Muller et al. 1997) of the subducting lithosphere, minimum slip vector residual (Liu et al. 1995, Khan 2007), intermittent occurrence of megathrust earthquake (1797 M  $\sim 8.4$ , 1833 M  $\sim 9.0$ , 1861 M  $\sim 8.5$ , Lay et al. 2005;  $M_w > 9.0$ , 2005  $M_w$  8.6, Ammon et al. 2005, 9.3; Stein and Okal 2005), and recently proposed strain-hardened model for mega-earthquakes (Khan and Chakraborty 2009) allowed us for understanding the role of major plate-driving forces (Forsyth and Uyeda 1975) for the occurrence of 2004 off Sumatra event.

Recurrence of major seismic energy bursts (Ishii et al. 2005), activation of three isolated fault segments in the southern, central and northern part (Dasgupta et al. 2005), and identified high stress condition (Mishra et al. 2007; Walter and Amelung 2007) along the Andaman-Sumatra margin during the 2004 event do not support the sector-specific stationarity of coupling arises from seamounts/asperity subduction (Dmowska et al. 1996). Instead, the 2004 event can be identified in the backdrop of minimum stress obliquity (Khan 2007), lowest flexing depth, shallowest dip angle, and two-stage opening of Andaman Sea from the off Sumatra area (Khan and Chakraborty 2005). Further, a poor correlation between subduction dynamics and seismic coupling ( $\chi$ ) as reported by Pacheco et al. (1993) and a wide variation of  $\chi$  i.e. high to very high ( $\chi = 0.6$  to 1.00, Scholz and Campos 1995; Prawirodirdjo et al. 1997) intermediate (Christensen and Ruff 1988) and very low ( $\chi = 0.02$ – $0.05$ , Peterson and Seno 1984; Pacheco et al. 1993) allow estimation of major plate-driving forces in the Sumatra area. A causal relationship between these major plate-driving forces and the geodynamic processes established under the present study for the Andaman-Sumatra margin clearly indicates that 2004 off Sumatra mega-earthquake was not unexpected in this area.

### Late tertiary tectonics around Andaman-Sumatra region

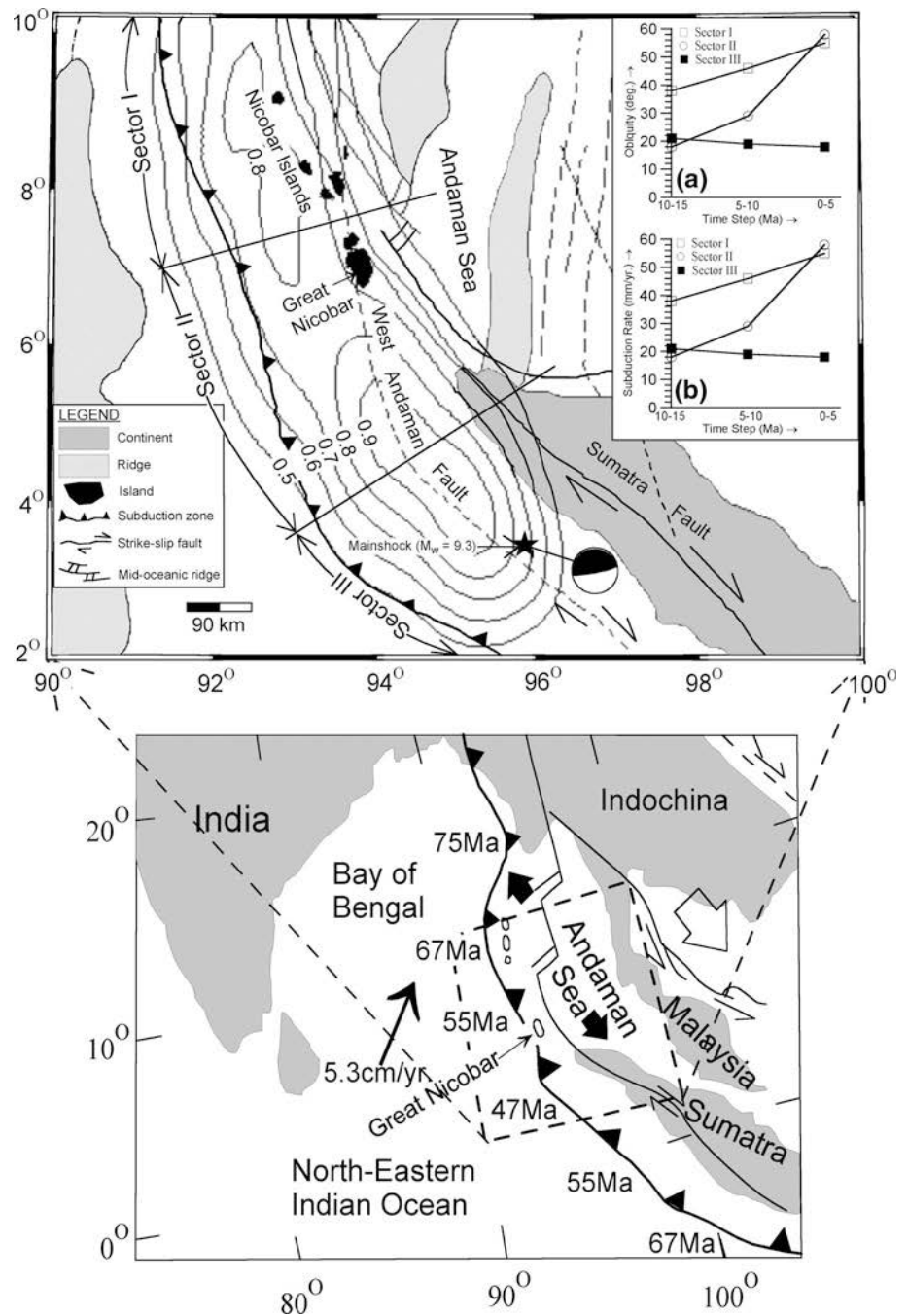
Sumatra margin, a transitional domain between the zones of frontal subduction of the Indo-Australian plate around Java towards east and oblique subduction of the Indian plate around Andaman towards north, recorded interference of multiple tectonic elements (Fig. 1), complex pattern of late Tertiary lithospheric deformation, and strong anomalous strain partitioning (Diament et al. 1992; Hall 1997; McCaffrey et al. 2000; Barber and Crow 2003; Metcalfe 2006). A  $\sim 40$  mm/year trench-normal convergence rate was recorded near the epicentre of 2004 off

Sumatra earthquake (Paul et al. 2001). Subsurface anomalous behaviour of the descending oceanic lithosphere with concomitant trench-parallel shifting of the Burma sliver plate and subsequent two-phase opening of the marginal basins in form of Mergui-Sumatra and Andaman Sea (Le Dain et al. 1984; Maung 1987; Raju et al. 2004; Khan and Chakraborty 2005) are the major late Tertiary geological events, and those were initiated from the northwest Sumatra and propagated towards north along the Andaman-Sumatra subduction margin. Enhanced convergence and increased plate obliquity (i.e. angle between converging plate velocity vector and normal to the trench) between the Indian and Eurasian plates (Fitch 1972; Patriat and Achache 1984), northward journey of the tangentially converging hanging Indian lithosphere through the surrounding asthenosphere (Le Dain et al. 1984; Curray 2005), clockwise rotation of the Sumatra-arc (Ninkovich 1976), and counter-clockwise rotation of north Sumatra and south Malaya (Hall 1997) resulted the offsetting of the Burma sliver plate (Le Dain et al. 1984; Maung 1987) and triggered the opening of the marginal basins. The opening of the Mergui and Andaman basins was accommodated along major strike-slip Sagaing fault in the north and Sumatra fault system in the south (Curray 2005). The change in direction of the northwestward opening of the Andaman Sea towards north and later northeastward was presumably associated with the fore-arc deformation (Khan and Chakraborty 2005) all along this margin. A temporary halt in rifting at the pull-apart opening stage and northeastward veering of the Andaman sea ridge (ASR) were apparently controlled by upliftment of oceanic crust in post-middle Miocene time in form of Alcock and Sewell seamounts, lying symmetrically north and south of this spreading ridge. The major geological incidences were concealed in the records of trench-normal segmentation all through the descending Indian lithosphere along the Andaman-Sumatra margin (Dasgupta et al. 2003).

### Benioff zone reconstruction

Earthquake data ( $m_b \geq 4.0$ ) those lying within the down-going oceanic Indian lithosphere and recorded at 15 or more stations between latitudes  $2.0^\circ$  and  $10.4^\circ\text{N}$  (Fig. 2) are considered for reconstruction of the Benioff zone configuration. The dataset were taken from ISC (International Seismological Centre) Bulletin covering the period between 1964 and 1999. The north–south extension of the study area is constrained by the 2004 off Sumatra mega-event rupture characteristics (Ammon et al. 2005; Ishii et al. 2005; Lay et al. 2005). For understanding the mutual interaction between the major plate-driving forces, the area was divided into three sectors on the basis of major seismic

**Fig. 1** Top map showing the tectonic framework of Nicobar–Sumatra margin (after Curry 2005; Curry and Munasinghe 1991). Bottom map showing the location of the study area. Note the age variation of descending oceanic plate along the Sunda margin (after Muller et al. 1997) in the location map. *Left bottom solid arrow* indicates Indian plate velocity vector, and *right top open arrow* is for major block motion with respect to Siberia since the Miocene. Solid star with beach ball represent the epicentre and focal mechanism of the mainshock. Contour lines (after Ishii et al. 2005) represent in percentage of the maximum seismic energy release associated with the Sumatra earthquake of 26 December 2004. Note the two major seismic energy bursts near Sumatra and Nicobar Islands with a minima near Great Nicobar. The *right top inset* in the top map shows the sector-specific variation of plate converging obliquity (a) and trench-normal subduction (b) in different time steps (after Khan and Chakraborty 2005)

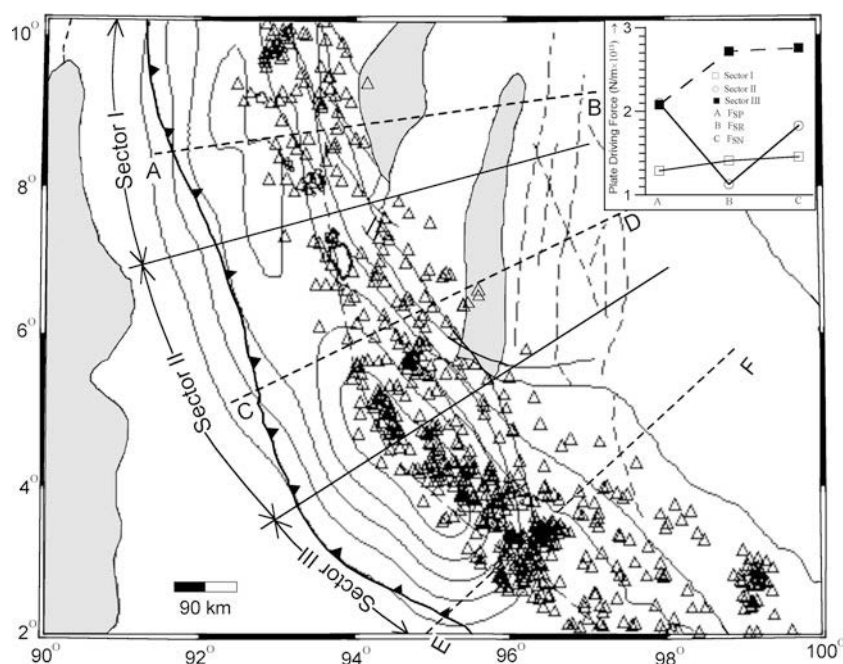


energy bursts during 2004 event (Ishii et al. 2005), pre-seismic stress fields (Khan 2007), and major geological incidences along this plate margin. The Benioff zone geometries in the three sectors were reconstructed based on the distribution of the intraplate historical earthquake data (Khan and Chakraborty 2005) and the age-dependent plate-thickness (expressed as  $2(kt_c)^{1/2}$ , where  $t_c$  is the age of the descending plate at the trench and  $k = 10^{-6} \text{ m}^2 \text{ s}^{-1}$  is the thermal diffusivity) (Conrad and Lithgow-Bertelloni 2002).

A literature survey for the Benioff zone reconstruction process using intraplate earthquake data reveals that the

procedures for delineating both upper and lower surfaces have some inherent inconsistency. The actual trend of the upper surface of the Benioff zone trajectory can be delineated with the best fit of hypocentral distribution (Ponko and Peacock 1995; Christova 2004). Instead, the delineation of lower surface can not reliably be determined using only hypocentral distribution as the seismogenic layer is limited and always less in thickness than the actual thickness of the descending oceanic lithosphere (Watts and Burov 2003). The delineation of the lower surface was thus demarcated by using both earthquake database (Fig. 2) and

**Fig. 2** Map showing the historical seismicity (*open triangle*) distribution. AB, CD, and EF are three profiles in the three sectors I, II, and III along which the high-resolution configurations of the Benioff zones (see Fig. 4) were reconstructed. Right top inset in the map showing the sector-specific magnitude of the down-dip component of slab pull force ( $F_{SP}$ ), slab-normal component of slab pull force ( $F_{SN}$ ), and slab resistive force ( $F_{SR}$ ). Note the excess values of  $F_{SR}$  over  $F_{SP}$  in sectors I (near Nicobar Islands) and III (near Sumatra), and the less values in sector II (near Great Nicobar)



well-defined plate age (Muller et al. 1997). The sector-specific configurations of the convection cells were reconstructed following the works of Kincaid and Sacks (1997). The cell concentration in the mantle wedge is likely constrained by the temperature, depth of serpentinisation of the fore-arc mantle (Kincaid and Sacks 1997; Hyndman and Peacock 2003), and sharp variation of dip (Khan and Chakraborty 2005).

### Implications of plate-driving forces

The journey of the oceanic lithosphere from constructive margins (e.g. mid-oceanic ridges) to consuming margins (e.g. subduction zones at the plate margin) is presumably controlled by a variety of plate-driving forces viz. ridge push ( $F_{RP}$ ), slab pull ( $F_{SP}$ ), slab resistive ( $F_{SR}$ ), basal drag/mantle drag ( $F_{DR}$ ), and trench suction ( $F_{SUC}$ ) (McKenzie 1969; Forsyth and Uyeda 1975; Harper 1975; Solomon et al. 1975). The ridge-normal push force is generally originated around the ridge crest due to elevated topography through cooling and thickening of the oceanic lithosphere (Forsyth and Uyeda 1975) and is estimated to be small enough (of the order of  $10^{12}$  N/m, Harper 1975; Parsons and Richter 1980) compared to slab pull force, sometimes less than  $\sim 10\%$  (Lithgow-Bertelloni and Richards 1998). Slab pull force arises from negative buoyancy of the oceanic lithosphere during penetration into the mantle and is reported to be a major plate-driving force that causes the motion of the plate (McKenzie 1969; Forsyth and Uyeda 1975; Harper 1975; Solomon et al. 1975), and estimated as an order of magnitude larger than

$F_{RP}$  (Turcotte and Schubert 1982). Besides the negative buoyancy force, the slab, during penetration into the mantle, experiences resistance due to viscous drag. The viscous drag/slab resistive force is estimated to be very large, comparable to the order of slab pull force (Forsyth and Uyeda 1975).

The surface plate at the trench and the deeper slab in the mantle experience the mutual interaction of the slab pull and slab resistive forces, and thereby, the slab penetrates into the mantle under the control of these forces (Richardson 1992). The penetration velocity either less (if  $F_{SR} < F_{SP}$ ) or greater (if  $F_{SR} > F_{SP}$ ) than terminal velocity (Isacks and Molnar 1971; Forsyth and Uyeda 1975). On the other hand, the basal drag/mantle drag force is small and poorly constrained (Richardson et al. 1979), and the trench suction force (a fraction of the slab pull force, Scholz and Campos 1995) generally arises due to dynamic motion of the convection cells and causes both the subducting and overriding plates to move towards trench axis. Moreover, the slab pull and slab resistive forces are an order of magnitude more than the other forces (c.f., Table 6 of Forsyth and Uyeda 1975). In the present study, these two major forces were quantitatively assessed along the Andaman-Sumatra margin, and their controls on the trench-parallel rupture propagation vis-à-vis occurrence of 2004 mega-event were investigated.

### Estimation of slab pull and slab resistive forces

Owing to the significance of plate-driving forces around the Sumatra margin, we estimated the forces acting on the



slab as (1) velocity-independent slab pull force, and (2) velocity-dependent slab resistive force (Forsyth and Uyeda 1975). The slab pull force along the length of the descending slab, resulted from negative buoyancy, can be expressed as

$$F_{SP} = \Delta\rho \cdot g \cdot V \cdot \sin\delta_{av} \quad (1)$$

where  $F_{SP}$  is taken towards down-dip direction of the slab, and the slab normal downward component of  $F_{SP}$  (i.e.  $F_{SN} = \Delta\rho \cdot g \cdot V \cdot \cos\delta_{av}$ ) is balanced by hydrodynamic lifting torque generated by a reactive flow in the mantle wedge above the slab (Turcotte and Schubert 1982; Scholz and Campos 1995) and control its dip during penetration into the mantle (Hager and O'Connell 1978).  $\Delta\rho$  is the density contrast between descending lithospheric slab and surrounding asthenosphere,  $g$  acceleration due to gravity, and  $V$  volume of the slab. The densities of the lithosphere and asthenosphere are not well constrained. However, the density contrast  $\Delta\rho$  can be well determined based on observed subsidence of the sea floor with plate cooling (cf. Fig. 1 of Cloos 1993). This allowed us to determine the variation of density contrast with lithospheric thickness, and hence  $\Delta\rho$  was estimated for the Sumatra margin. Volume of the slab ( $V$ ) in the three sectors (I, II and III) was estimated using basic software.

The slab resistive force, which opposes the motion of the descending slab into the mantle, is expressed as

$$F_{SR} = 6\pi\eta_{av}r_e v_s \quad (2)$$

where  $\eta_{av}$  is the average viscosity over the depth range of the slab,  $r_e$  is the effective radius of the slab, and  $v_s$  is the trench-normal subduction rate (Table 1). Viscosity is another very fundamental parameter, like density, for the earth's inner material, and again very poorly constrained.

**Table 1** Sector-specific computed parameters, related to subduction of the oceanic Indian lithosphere, were used to estimate the slab pull force ( $F_{SP}$ ), slab-normal force ( $F_{SN}$ ), and slab resistive force ( $F_{SR}$ )

	Sector I	Sector II	Sector III
Volume of the hanging slab ( $V$ ) ( $\text{km}^3 \times 10^7$ )	1.07	1.32	0.8
$r_e$ (km)	136.9	146.8	124.8
$v_s$ (mm/s)	36.55	34.01	39.16
$\delta_{av}$ (deg.)	41.3	48.9	37.0
Thickness of the slab (km)	90.6	83.3	77
Average depth of penetration of the slab (km)	155	272	215
$\eta_{av}$ ( $\text{Pa} - \text{s} \times 10^{21}$ )	1.87	1.43	1.87
$\Delta\rho$ ( $\text{kg/m}^3$ )	73.5	80.7	87.1
$F_{SP}$ ( $\text{N/m} \times 10^{13}$ )	1.29	2.10	2.08
$F_{SN}$ ( $\text{N/m} \times 10^{13}$ )	1.46	1.83	2.76
$F_{SR}$ ( $\text{N/m} \times 10^{13}$ )	1.41	1.13	2.72

There are basically two independent approaches available to understanding the viscosity profile within the Earth: (1) parameters related to isostatic adjustment over the time frame of glacial cycles (Nakada and Lambeck 1989; Mitrovica 1996; Mitrovica and Forte 2004), and (2) data related to physical deformation properties linked to the convection processes (King and Masters 1992; Corrieu et al. 1994; Panasyuk and Hager 2000). Both the methods have some advantages and drawbacks, and hence the depth variation of mantle viscosity was reconstructed several times (Mitrovica 1996; Mitrovica and Forte 2004). It is therefore realistic to appreciate the mantle viscosity profile computed by Mitrovica and Forte (2004) on the basis of non-linear, iterative, Occam-style joint inversions of extensive data set (e.g. shorter wavelength gravity anomalies, the dynamic surface topography, horizontal divergence of plate motions, and the Fennoscandian relaxation spectrum) associated with mantle convection and glacial isostatic adjustment (GIA), and this well-derived viscosity profile was used in the present study for estimating the value of  $\eta_{av}$ .

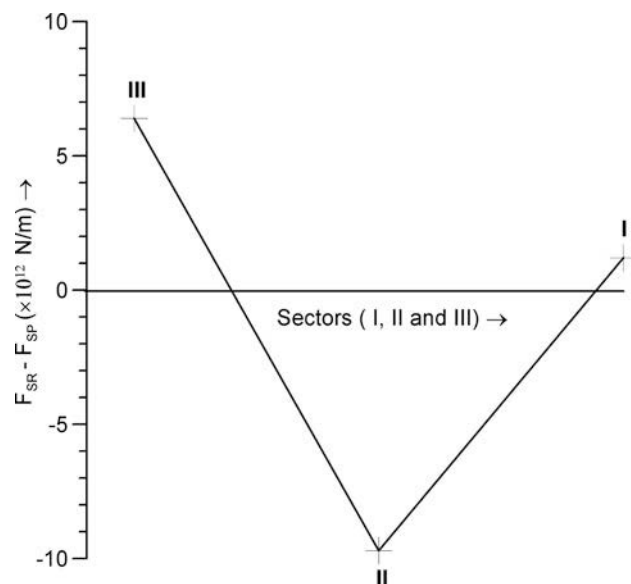
The effective radius of the slab can be estimated either through approximation of edgewise translation of an ellipsoid through a viscous medium (Lamb 1993; Scholz and Campos 1995) or equivalence to the volume of a rigid sphere. Moreover, the inconsistent configurations of the subducting slabs allowed us for deriving the effective radii of the slabs in the three sectors (Table 1) through the following equation

$$r_e = \left(\frac{3V}{4\pi}\right)^{\frac{1}{3}} \quad (3)$$

## Results

The computed values of plate-driving forces along the Andaman-Sumatra margin are illustrated in Table 1. The value of  $F_{SP}$  (down-dip component of the slab pull force) is the smallest (i.e.  $1.29 \times 10^{13}$  N/m) in sectors I (near Andaman) and the largest (i.e.  $2.10 \times 10^{13}$  N/m) in sector II (near Great Nicobar), respectively. Value of  $F_{SP}$  in Sector III (near Sumatra) is nearly equal to that of sector II. In contrast, the value of  $F_{SR}$  is the largest (i.e.  $2.72 \times 10^{13}$  N/m) in sector III, and the minimum value (i.e.  $1.13 \times 10^{13}$  N/m) is noted in sector II. While the intermediate  $F_{SR}$  value (i.e.  $1.41 \times 10^{13}$  N/m) is noted in sector I. The wide variation of both these forces is apparently complied with the inhomogeneous trench-parallel rupture, seismic energy bursts (Ishii et al. 2005; Lay et al. 2005; Ammon et al. 2005; Mishra et al. 2010), dip of the descending oceanic lithosphere (Khan and Chakraborty 2005), and trench-normal subduction rate (Fig. 1). It can further be demonstrated that the relative extent between

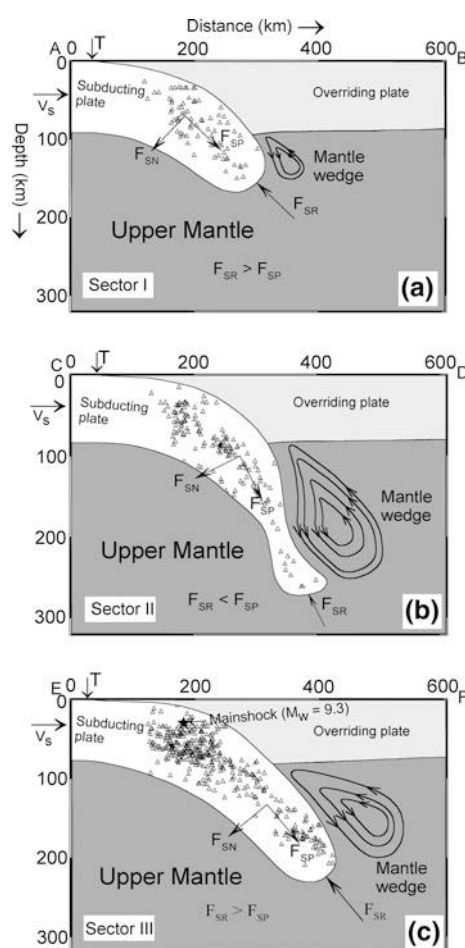
$F_{SR}$  and  $F_{SP}$  (Fig. 3) is also varied reasonably in the three sectors, and  $F_{SR} - F_{SP}$  is positive in sectors I and III, and vice versa in sector II. The least value of  $F_{SR} - F_{SP}$  ( $0.12 \times 10^{13}$  N/m), and higher dip of the descending lithosphere (Khan and Chakraborty 2005) in sector I apparently comply with the occurrence of relatively smaller magnitude earthquakes towards north (discussed before) around Andaman area and also support the absence of intermediate-depth aftershocks following the 2004 Sumatra mega-event (Mishra et al. 2010). Here, the descending lithosphere in this area is possibly decoupled from the overriding plate (e.g. northeast Japan forearc, Mishra et al. 2003). The comparatively lower seismic energy burst during 2004 earthquake (Ishii et al. 2005) in Andaman area also corroborates this observation. Instead, the negative value of  $F_{SR} - F_{SP}$  (Figs. 1, 3) accounts for the minimum seismic energy burst near Great Nicobar area (sector II), and the slab is presumably being supported from surface plate at the trench. Alternatively, the highest positive value of  $F_{SR} - F_{SP}$  in sector III led the descending slab being supported from below in the surrounding mantle (Forsyth and Uyeda 1975; Conrad and Lithgow-Bertelloni 2002), and the shallower part (e.g. flexing zone) of the lithosphere experiences compressive stress field. This is presumably due to superposition of pulsating stresses on the long-term time average or steady bending stresses (Rice and Stuart 1989; Taylor et al. 1996; Khan and Chakraborty 2009) along the longitudinal profile of the descending oceanic slab in Sumatra area (sector III). The pulsating periodic stress was clearly initiated from the uncompensated slab resistive force (Christensen and Ruff 1988; Astiz et al.



**Fig. 3** Plot showing the sector-specific relative extent between slab resistive and slab pull forces (i.e.  $F_{SR} - F_{SP}$ )

1988; Lay et al. 1989). It is also appreciated in the literature (Forsyth and Uyeda 1975) that the mutual interaction between  $F_{SR}$  and  $F_{SP}$  along the longitudinal profile of the descending lithosphere is responsible for generating either extensional or compressional earthquakes at shallow depths for  $F_{SR} < F_{SP}$  or  $F_{SR} > F_{SP}$ , respectively. It was also observed elsewhere that the local intraslab seismicity is occasionally being evolved by the interaction between local tectonics and bending stresses (Mishra and Zhao 2004). This may allow for more interdisciplinary research to better understanding the tectonics, rheology, and stress state of the subducting slabs.

The reconstructed Benioff zones shown in Fig. 4 illustrate the operation of slab resistive force and down-dip and normal component of slab pull force on the hanging



**Fig. 4** Model indicates the penetration of the oceanic Indian lithosphere, reconstructed through distribution of hypocenters, and subducting plate age, into the mantle in the three sectors I, II, and III.  $F_{SP}$ ,  $F_{SN}$ , and  $F_{SR}$  acting within the descending lithosphere are represented by arrows.  $V_s$  represents the trench-normal subduction rate. Convection cell trajectories were reconstructed after the works of Kincaid and Sacks (1997) and Hyndman and Peacock (2003). Note the sector-specific trade-off between  $F_{SP}$  and  $F_{SR}$ .  $T$  in the model represents the sector-specific location of the trench

lithosphere in three sectors along the Andaman-Sumatra margin. Oceanic lithosphere generally descends into the mantle with near-terminal velocities at most subduction margins around the world (Forsyth and Uyeda 1975). However, a comparison between trench-normal subduction rate and angle of subduction based on corner flow model (Stevenson and Turner 1977; Tavis et al. 1978) commonly indicates a steady equilibrium of a subducting lithosphere at a particular angle greater than the critical angle ( $\theta_c = \sim 63^\circ$ ) after attaining a specific negative buoyancy force. However, for dip with less than critical value (i.e.  $\theta_c < 63^\circ$ ) the descending lithosphere can never achieve its stability (Stevenson and Turner 1977), and moreover, experiment (Guillou-Frottier et al. 1995; King 2001) indicates that subduction is not a steady phenomenon, and significant deformation of the slab at different depth level is inevitable. It is thus may be summarized that the slab may undergoes unstable equilibrium with significant deformation for dipping angle less than its critical value, and this critical condition can sometimes be achieved by hydrodynamic lifting towards the overriding plate. However, the hydrodynamic lifting force is generally balanced by counter action of  $F_{SN}$  (Forsyth and Uyeda 1975). In any case, the shallower dips ( $\theta_c < 63^\circ$ ) of the slabs (Fig. 3 of Khan and Chakraborty 2005) in sectors II and III clearly account for instability of the descending lithosphere, and the relative extent of  $F_{SR}$  over  $F_{SP}$  (i.e.  $F_{SR} - F_{SP} = 0.64 \times 10^{13}$  N/m, refer Table 1) in sector III might be responsible for the occurrence of 2004 off Sumatra mega-event. Higher dip of the slab towards its northernmost sector possibly allowed volcanicity around the Barren and Narcondum areas and that somehow caused crustal weakening during enhanced convective circulation process in the mantle wedge (cf. Zhao et al. 2002) leading to an energy burst during 2004 event around North Andaman area (Ishii et al. 2005; Mishra et al. 2010).

## Discussion

The geodynamic processes at the converging plate boundaries are generally complicated. The trench-normal component of the convergence allows the slab to sink into the mantle, and the trench-parallel component leads the tangential motion of the slab. Therefore, the plate obliquity plays an important role in reconstruction of the tectonic setting along oblique subduction margin. Further, the penetration of the converging plate into the mantle is primarily controlled by the balance of forces acting on the descending slabs, and the major plate-driving slab pull force is normally emphasized to account for the shallow-level intraplate down-dip extensional failures (Christova and Scholz 2003; Seno and Yoshida 2004). The megathrust

failure instead are interpreted in terms of either interplate coupling or seamounts/asperity subduction, and the effect of slab resistive force behind the occurrence of large earthquakes along subduction margins was hardly addressed. Moreover, the interplate coupling and/or seamount subduction hypotheses remained conjectural as studies by different workers resulted contradictory viewpoints (Christensen and Ruff 1988; Pacheco et al. 1993). Besides, fore bearers of asperity subduction hypothesis (Ruff and Kanamori 1983; Cloos and Shreve 1996) noticed coincidence of distinct bend in Benioff zone configuration with the most active zone of seismic slip accumulation in many of the subduction margins around 30–40 km depth. The high-resolution reconstruction of depth-dip angle profiles across the Sumatra margin (Khan and Chakraborty 2005) showed minimum dip and attainment of early (around 25 km depth) dip angle saturation in Benioff zone trajectory in sector III, and the slip/stress vector residual was noted to be minimum (nearly zero, Liu et al. 1995; Khan 2007). It is therefore may be proposed that the occasional incidences of great earthquakes around Sumatra plate margin were somehow associated with the spatio-temporal changes of the plate obliquity, subduction rate, and depth of plate flexing (Khan and Chakraborty 2005). Trench-parallel thrust dominated movements in sector III and trench-parallel shear dominated movements in sector II under static stress field (Khan 2007) also comply with the dynamic imbalance between  $F_{SP}$  and  $F_{SR}$ , and the net force (i.e.  $F_{SR} - F_{SP}$ ) estimated in sector III rightly indicates higher compressive stress accumulation within the shallower part (i.e. flexing zone) of the descending lithosphere.

Occasional incidences of great earthquakes over a span of last 200 years and recurrence of seismic energy burst during the 2004 off Sumatra mega-event can further be visualized in the backdrop of major late Tertiary geological events along this Andaman-Sumatra margin. Large-scale subsidence of the forearc and opening of Mergui-Sumatra basin near the northwest Sumatra were interpreted in terms of late Oligocene deformation of the descending lithosphere. Further, the region in the vicinity of southeast Sumatra documents plate obliquity just greater than its critical value and that triggered the trench-parallel shear motion. The late Miocene-Pliocene pull-apart opening of the Andaman Sea from the same area was also associated with the anomalous deformation of the lithosphere (Khan and Chakraborty 2005). Moreover, the region records minimum dip (less than critical value) of the descending lithosphere over this entire Sunda margin. These features usually allow the slab to accumulate more stress around the flexing zone resulting from dynamic imbalance between  $F_{SR}$  and  $F_{SP}$  over decades, and occasionally released through intraplate shallow-level thrust failure in the descending slab around the Sumatra region. It is thus

proposed that the plate-driving forces had a definite control on the occurrence of 2004 off Sumatra event and apparently associated with shallow-level flexing zone of the lithosphere. A causal relationship between these major plate-driving forces and the geodynamic processes established under the present study for the Andaman–Sumatra margin clearly indicates that 2004 off Sumatra mega-earthquake was not unexpected in this area.

## Conclusions

We have estimated the major plate-driving forces i.e. slab pull and slab resistive in three specific sectors along the Andaman–Nicobar–Sumatra subduction margin and found a strong correlation between the seismic energy burst and unbalanced components of these forces. We propose that the bending stress around the flexing zone was enhanced by the superimposition of excess slab resistive force in Sumatra sector. The combined stress around the flexing zone subsequently exceeds the yield point stress of the material and provoked thrust movement along a shallowly dipping ( $\sim 8^\circ$ ) plane releasing maximum energy on 26th December 2004. The release of seismic energy suddenly drops to a minimum towards north near Great Nicobar where the descending plate was documenting tension at the shallower part. Farther towards north, the flexing zone of the trench-hanging lithosphere recorded a little excess of slab resistive force where the third seismic energy burst was identified. The mutual interaction between enhanced convective circulation in the mantle wedge and the stress field in the flexing zone might have a positive role behind the generation of lower seismic energy burst near North Andaman.

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